Rejection of Bluetooth Interference in 802.11 WLANs

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Abstract - We investigate the use of complex coefficient adaptive filters for interference suppression in the direct sequence spread spectrum 802.11 system. Extensive simulations are carried out to optimize the parameters of a recursive least-squares lattice filter, which mitigates the effect of a hopping narrow-band interferer such as Bluetooth. The BER curves, as well as the probability of packet loss, are presented. Moreover, the limitations of the adaptive filter approach, in the suppression of multiple jammers, is determined. It is shown that with a low order filter, the hopping jammer can be successfully suppressed.

I. Introduction

With the coming deployment of new wireless personal area networks in the 2.4 GHz ISM band, there is a growing concern about coexistence with existing systems, especially the IEEE 802.11b wireless local area network (WLAN). These systems can seriously damage the operation of the WLAN system [1]. For instance, the BT system occupies a 1 MHz bandwidth, and it has 79 hopping channels [2]. A direct sequence spread spectrum (DSSS) 802.11b system occupies approximately 22 MHz in the same band. Therefore, the BT system will consistently hop into the 802.11b spectrum, causing unintentional interference to both. Given the importance of coexistence between BT and 802.11, there has been considerable research on this topic. An overview of some of the proposed approaches is given in [3]. Most of these methods concentrate on changing the MAC layer behavior, such as by rescheduling packets or otherwise altering the traffic. Some of the approaches are collaborative, requiring a dual Bluetooth and 802.11 receiver.

This paper suggests a non-collaborative approach, based on signal processing in the physical layer. Specifically, we propose interference rejection for the DSSS WLAN using recursive least-squares lattice filters. Since the WLAN has no *a priori* knowledge of the timing or frequency used by the Bluetooth interference, it uses the adaptive filter to estimate and cancel the Bluetooth interference. While this paper focuses on the 1 Mb/s 802.11 mode, the suppression method is also applicable to the 2 Mb/sec QPSK DSSS mode. Moreover, the results can be extended from Bluetooth interference to other narrow-band networks such as HomeRF and the frequency-hopping IEEE 802.11 WLAN.

There has been much research in the area of interference suppression filters; for a recent review please see [4], *cf.* [5] [6] [7]. These papers, to our best knowledge, prominently consider a strong fixed frequency interferer in the bandwidth of the desired signal. There is not as much information in the open literature about the performance of these filters for a hopping jammer. Consequently, this paper studies a new application for these filters in a dynamic environment with hopping interference. In a wireless network environment, a long WLAN packet may be subject to multiple BT interferers, each with a different frequency offset and amplitude. For each interference, the adaptive filter coefficients have to change to compensate for the new conditions. For multiple simultaneous interferers, this is a challenging task. The lack of error correction in the WLAN packets adds to the difficulty, since even one bit error will lead to packet loss. Therefore, the interference suppression algorithm has to detect and cancel the interference in less than one bit interval. On the other hand, for short distance indoor applications, one can assume that the carrier-to-noise ratio (CNR) is high. This helps to speed up the convergence rate for some particular algorithms.

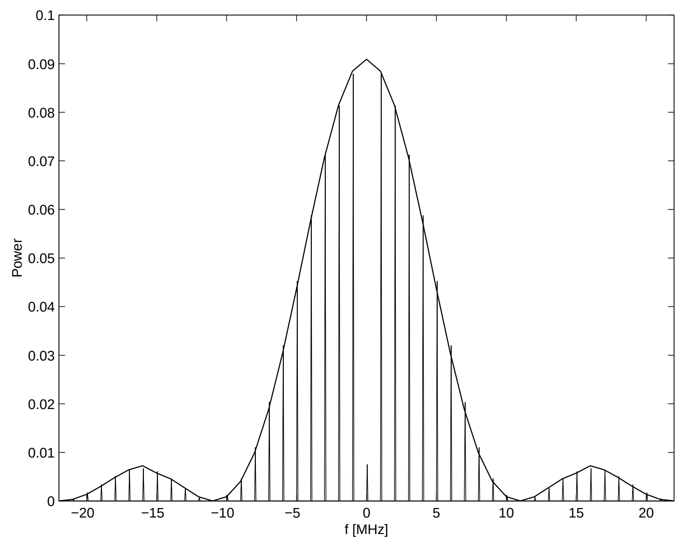

Fig. 1. Frequency spectrum of the Barker code; the frequencies are relative to the center frequency, which is labeled as 0 MHz. Note the notch of approximately 10 dB at the carrier frequency.

II. WLAN System Model

The 1 Mb/sec DSSS 802.11 WLAN employs DBPSK modulation, and each bit is spread by an 11 chip Barker code [8]. Fig. 1 shows the transmitted signal spectrum, which has a substantial notch at the carrier frequency; an analytical derivation of the spectrum is given by Lee and Miller [9]. As will be shown below, this notch is the reason

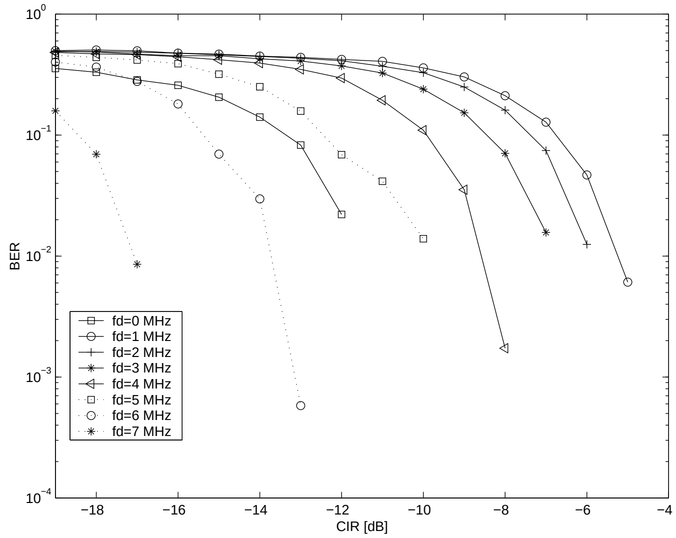

Fig. 2. Bit error rate performance of the 802.11 receiver in the presence of Bluetooth interference. CNR = 35 dB.

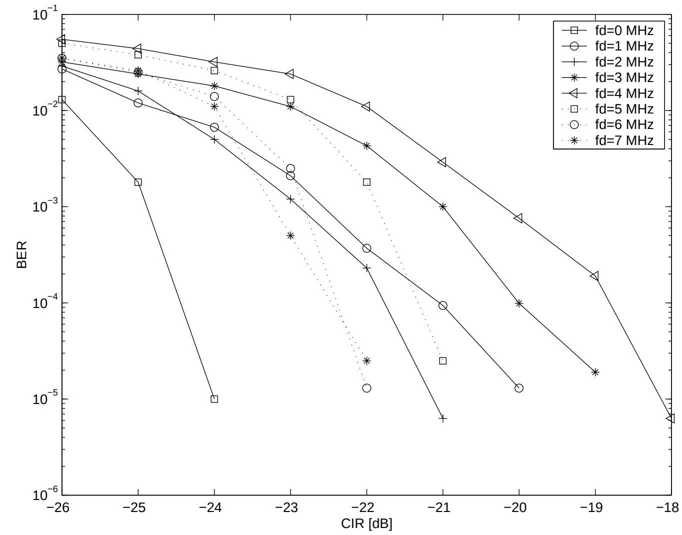

Fig. 3. RLSL algorithm. One BT interferer. CNR = 35 dB.

that the performance of the 802.11 receiver with Bluetooth interference at zero frequency offset is better than the performance with the interference at 1, 2, 3, or 4 MHz offsets.

The discrete input signal to the WLAN receiver, sampled once per chip period, T_c, can be expressed as

$$x(k) = s(k) + i(k) + n(k), \quad k = 1, 2, \cdots. \tag{1}$$

Here, $s(k)$ is the desired 1 Mb/sec DSSS WLAN signal with DBPSK modulation, $i(k)$ is the BT interference, and $n(k)$ is the additive white Gaussian noise. There are 11 complex samples/bit in the baseband signal, because of the 11 chip Barker code [1].

Fig. 2 depicts the BER curves for the above system, obtained using Monte Carlo simulation. We assume an interference-limited environment with $CNR = 35$ dB. In these plots, f_d is the frequency offset between the WLAN carrier and the BT interference. We suppose that the interference is always on and that it exists for the entire length of the WLAN packet. The carrier-to-interference ratio (CIR) is defined before the bandpass filter at the receiver. One sees that a CIR value less than -4 dB is capable of producing errors in the WLAN packet. The details of the simulation can be found in [1].

III. Adaptive Filter Results

While we have obtained good results using an adaptive filter based on the least-mean square (LMS) algorithm, we choose to focus on the recursive least-squares lattice (RLSL) filter. The RLSL algorithm requires more computational complexity than the LMS algorithm, but its fast convergence rate makes it attractive for interference suppression. This algorithm is described in [10], and for the sake of the brevity, it is not repeated here. The parameters of the algorithm are M, which is the order of the lattice filter, and λ, which is the forgetting factor. λ represents the memory of the algorithm, with $\lambda = 1$ corresponding to infinite memory. For one interferer, it was observed that even $M = 1$ would be enough to cancel the interference. However for multiple simultaneous interferers, increasing M to some extent will decrease the BER. We employ $M = 3$ and $\lambda = .97$ for these simulations.

Fig. 3 presents the results for one BT interferer. For $CNR = 35$ dB, one sees that the RLSL algorithm is capable of reducing the BER to below 10^{-2} for CIRs as low as almost -22 dB. It is worth noting that the interference at 3 and 4 MHz offsets is the most difficult to suppress, because the Bluetooth signal is right in the middle of the main lobe. A CIR of -20 dB gives a BER of 10^{-3}, a gain of almost 15 dB compared to the baseline case of Fig. 2. Even when the CNR is only 15 dB, the RLSL filter brings the BER below 10^{-3} for CIRs of -15 to -16 dB (no shown).

IV. Multiple BT Interferences

Fig. 4 illustrates the BER performance for two BT interferers. The abscissa shows the CIR of the second interferer, and the three curves are for different CIRS of the first interferer. Even if the CIR compared to the first interferer is -20 dB, a BER of 10^{-3} is achieved if the CIR compared to the second interferer is -10 dB.

If the number of time-overlapping BT interferers is more than two, it is still possible for adaptive algorithms to suppress all the interference at certain combinations of frequency offsets. For instance, for three equal power jammers, our simulations showed that at some frequency offsets the RLSL filter could achieve $BER \leq 10^{-3}$ at CIR

[1] In the simulations, 4 samples/chip are used to allow a frequency offset between the WLAN and BT without aliasing. However, the sampling rate is properly reduced by the receiver.

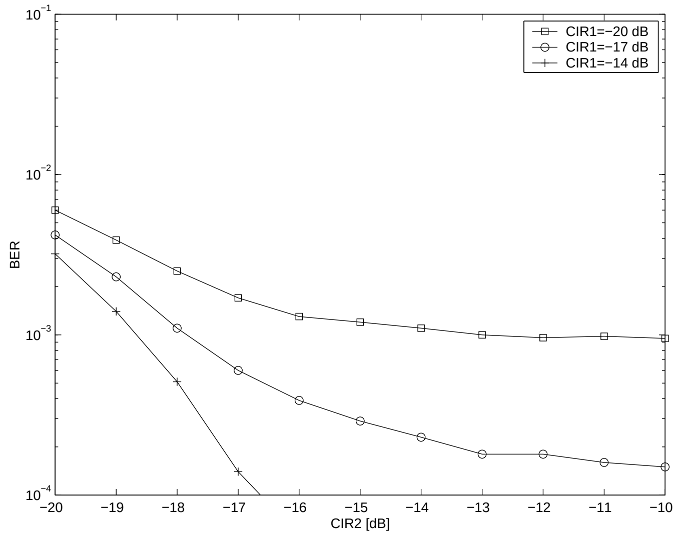

Fig. 4. BER for multiple Bluetooth interferers.

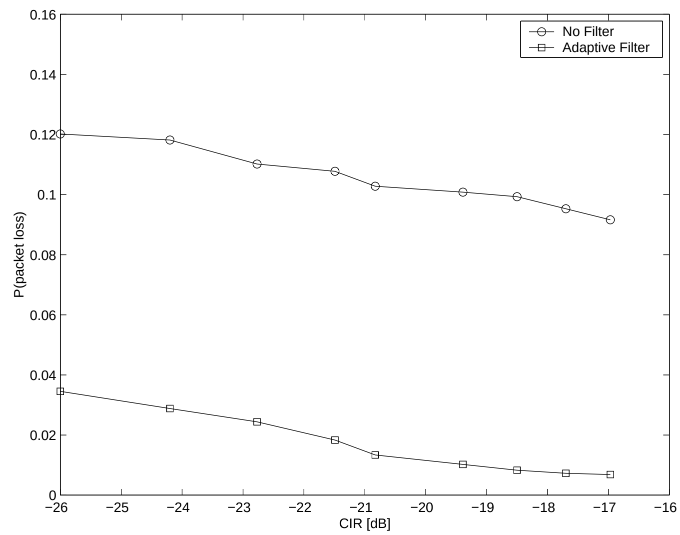

Fig. 5. Packet loss probabilities with and without the use of the adaptive interference suppression filter.

values as low as $CIR1 = CIR2 = CIR3 = -10$ dB. However, for all possible combinations of frequency offsets, the filter does not increase the performance that much unless the CIR is high enough, ($CIR = -4$ dB). This value is close to the minimum tolerable CIR value for the WLAN receiver with no interference rejection filter.

V. Packet Loss Probability

Perhaps of more interest is the effect that the interference suppression filter has on the probability of packet error. This MAC layer statistic is important, since packets with errors need to be retransmitted. Fig. 5 shows the loss probabilities for a Bluetooth interferer for two cases. The first case is for the baseline system, while the second case uses the RLSL adaptive filter. Over a large range of CIRs, the adaptive filter is able to reduce the loss rate from 10 to 12 percent to 1 to 3 percent, significantly improving the system throughput.

VI. Conclusions and Present Work

In this study, we show that an RLSL adaptive filter can be used in order to suppress a hopping Bluetooth interferer. For a single jammer, the algorithm performs quite well, and it can effectively cancel a hopping jammer at different frequency offsets. The RLSL algorithm substantially reduces the BER for two simultaneous jammers, and depending on the actual time and frequency overlap, the packet may be error free. Three simultaneous interferers is a more difficult problem, but even here the adaptive filter substantially improves the performance. Further results for these cases will be shown in the final paper.

There are two extensions to this work. The first one is to develop a receiver architecture, including the adaptive filter, that performs well for multi-path fading channels. Initial results, using a non-coherent combining RAKE receiver with an adaptive filter, are promising. The next extension of this work is to use an adaptive interference cancellation mechanism to mitigate the effect of Bluetooth on the 5.5 and 11 Mb/s 802.11b modes. Since these modes use complementary code keying (CCK), instead of DSSS, one must consider the combined effects of the interference suppression filter and the equalizer in the receiver design.

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